Electrodynamic Tethers for Exploration of Jupiter and its Icy Moons

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Abstract

Use of electrodynamic bare tethers in exploring the Jovian system by tapping its rotational energy for power and propulsion is studied. The position of perijove and apojove in elliptical orbits, relative to the synchronous orbit at 2.24 times *Jupiter*'s radius, is exploited to conveniently make the induced Lorentz force to be drag or thrust, while generating power, and navigating the system. Capture and evolution to a low elliptical orbit near *Jupiter*, and capture into low circular orbits at moons Io and Europa are discussed.

1. Introduction

A full study of the giant, complex Jovian system is a central goal in space science [1]. There exists a pressing need for a spacecraft (S/C) to reach into a low orbit around moon *Europa*, as well as around moon Io and *Jupiter* itself. Within such a scope, the successful Galileo mission was a handcuffed mission. The need of gravity assist manoeuvres (GAMs) to reach *Jupiter* resulted in quite restricted launch windows and a protracted trip. Just the capture operation required too much chemical propellant, reducing scientific payload to a few percent in mass. The power source used, Radioisotope Thermal Generators (RTGs), is too weak. Capabilities for orbit manoeuvring after capture and for data transmission were very low [2].

In 1999 the US National Research Council made full scientific planning for a mission to *Europa*, which would still use RTG's for power, and use gravity assists for a Jovian moon tour supposedly acquiring a low *Europa* orbit in a few months [3]; escalating costs, however, made NASA cancel the mission in 2002. At about that time, NASA embarked in *Project Prometheus* on the use of nuclear reactors for both power, and powering electrical thrusters (NEP). Original planning for a *Jovian Icy Moons Orbiter* (an "unfriendly", 20 ton system), gave later place to *Juno* (polar Jovian) and *Neptune-Triton* missions.

ESA in turn has made plans about a *Jovian Minisat Explorer*, which would keep some *Galileo* features (GAMS-determined trip from *Earth*, chemical-rocket capture) but move back from RTG's to solar arrays. ESA considers developing *Low Intensity Low Temperature* cells with solar concentrators. Should that program fail, ESA would revert to RTG's, which are socially problematic however. Also, Pu-238 oxide is scarce and expensive (10^6€/ kg) and ESA must face ITAR restrictions on US RTG technology. On reaching *Jupiter*, the *JME* would split into a *Jovian Relay Satellite* and a *Jovian Europan Orbiter* due to acquire a low *Europa* orbit through an extended series of GAMS in 550 days [4].

The approach here discussed would involve neither RTG's, nor nuclear reactors or solar arrays. It would use an electrodynamic (ED) tether system, accounting for a moderate fraction of S/C mass, to tap *Jupiter*'s rotational energy for **both** power and propulsion [5, 6]. It should result in a direct trip from *Earth* and higher data-handling and scientific payload capabilities, and it would allow for a fast manoeuvring, 'free-lunch' tour (using GAMs and chemical propulsion very sparingly). Since tether performance is dependent on ambient conditions (magnetic field B and plasma density N_e), the critical phase is S/C capture. Ambient model uncertainties would suggest launching two light S/C, one designed for nominal conditions, the other with greater design margins; as a bonus, they would make possible determining spatial structure in the extensive Jovian magnetosphere.

2. Power Generation, Drag and Thrust at an ED-Tether

Consider a simple planet/light-satellite system. Both planetary spin and orbital motion contribute to mechanical energy,

$$\epsilon_{mech} = \frac{1}{2} I_{pl}\omega_{pl}^2 - \frac{\mu_{pl} M_{sat}}{2a} \tag{1}$$

and to angular momentum

$$H = I_{pl}\omega_{pl} + \frac{\mu_{pl} M_{sat}}{2a\Omega_{orb}} \tag{2}$$

With H = const $\equiv H_0$, Kepler's law $a^3\Omega_{orb}^2 = \mu_{pl}$ determines $\epsilon_{mech}(a; H_0)$,

$$\frac{2a_*\epsilon_{mech}}{\mu_{pl} M_{sat}} = \left(\frac{H_0}{I_{pl}\sqrt{\mu_{pl}/a_*^3}} - \sqrt{\frac{a}{a_*}} \right)^2 - \frac{a_*}{a} \tag{3}$$

where a_*^2 is $\frac{I_{pl}}{M_{sat}}$ and where we assumed a circular equatorial orbit with $\mathbf{\bar{H}_0} \cdot \mathbf{\bar{\Omega}_{orb}} > 0$.

If $3^{3/4}H_0 > 4I_{pl}(\mu_{pl}/a_*^3)^{1/2}$, the graph $\epsilon_{mech}(a)$ presents a maximum, and a minimum farther out, both extrema corresponding to rigid-body motion, $\Omega_{orb} = \omega_{pl}$. The maximum is always unstable, any kinetic mechanism for dissipation (specifically, tidal forces) would drive the satellite away from rigid-body motion at a(max), on either side of it. For the comparatively extremely light artificial satellites, the maximum lies at the synchronous or stationary radius $a_{s,pl} \equiv (\mu_{pl}/\omega_{pl}^2)^{1/3}$ where a satellite corotates with the planet (the energy minimum lying beyond Universe limits even for multi-ton space stations). If one would have a corotating atmosphere beyond a_s, satellites at $a > a_s$ would be pushed by faster-moving air to higher (though slower) orbits, air thus exerting thrust rather than drag.

In planets that have both magnetic field and ionosphere/magnetosphere, an orbiting conductive tether provides an alternative dissipative mechanism. Consider the nonrelativistic equation for transformation of electric field,

$$\begin{aligned} \bar{E}(tetherframe) - \bar{E}(plasmaframe) \\ = \bar{E}_m \equiv (\bar{\nu}_{orb} - \bar{\nu}_{pl}) \wedge \bar{B} \end{aligned} \tag{4}$$

In the highly conductive plasma away from the tether, the electric field will be negligible in the frame moving with the corotating plasma, yielding, in the tether frame, $\bar{E}(outside) = \bar{E}_m$. This outside field will drive a current inside the tether, $\bar{I} \propto \bar{E}$ (inside, in tether frame), with $\bar{I} \cdot \bar{E}_m > 0$. Using Eq. 4 for E_m and the Lorentz force $L\bar{I} \wedge \bar{B}$, the net mechanical power in the tether-plasma interaction becomes

$$L\bar{I} \wedge \bar{B} \cdot (\bar{\nu}_{orb} - \bar{\nu}_{pl}) = -L\bar{I} \cdot \bar{E}_m < 0 \tag{5}$$

that lost power appearing in the tether electrical circuit. Clearly, $L\bar{I} \wedge \bar{B} \cdot \bar{\nu}_{orb}$ will be positive, corresponding to thrust acting on the tethered S/C, if $\bar{\nu}_{orb}$ is opposite $\bar{\nu}_{orb} - \bar{\nu}_{pl}$; this recovers the $a > a_s$ condition [6]. Figure 1 illustrates this condition for the tether-plasma interaction.

The basic requirement for quasisteady ED-tether operation is establishing effective contact, both anodic and cathodic, with the ambient plasma. Electron ejection is not an issue. Hollow cathodes are presently reaching ratios of current to expellant mass-flow rate as large as $10^2 A/mgs^{-1}$ (which is about the charge/mass ratio of protons). This results in fully negligible expellant consumption at a hollow cathode (HC): For $B \sim 1$ Gauss and a tether length L of tens of kilometres, the ratio of the Lorentz force to the expellant mass-flow-rate is well over 10,000 km/s, which is several orders of magnitude larger than the jet velocity of electrical thrusters.

As regards the problem of anodic contact with a highly rarefied plasma, it was solved in 1992 when it was proposed that, instead of using a big end collector, the tether be left bare of insulation, allowing it to collect electrons - as a cylindrical Langmuir probe in the orbital motion limited (OML) regime - over the segment coming out polarized positive [7]. A length-averaged tether current, $I_{a\nu}$, should now figure in the Lorentz force. The collecting area of a thin bare tether can be large because that segment may be tens of kilometres long. Collection can be efficient if the cross section dimension is smaller than both electron Debye length and gyroradius [8]. The cylindrical geometry allows a final bonus; a thin tape can collect the same current as a round wire of equal cross-section perimeter [9] and will be much lighter. The optimal tether is thus characterized by three quite disparate dimensions, $L \gg w$ (width) $\gg h$ (thickness).

3. The Jupiter Free-Lunch Tour

The Jovian system is a particularly appropriate place for using an ED-tether. The stationary orbit for a planet is readily shown to satisfy the relation

$$a_s/R_{pl} \propto (\rho_{pl}/\Omega_{pl}^2)^{1/3} \tag{6}$$

Jupiter has both low mean density ρ_J and rapid rotation; as a result the stationary orbit lies at $a_{sJ} \approx 2.24R_J$, which is one third of the relative distance for *Earth*. Further, the surface magnetic field is ten times greater at *Jupiter* than at *Earth*, magnetic pressure and tension thus being 10^2 times greater in *Jupiter*. A plasmasphere reaches to about $3.8R_J$, well beyond a_{sJ}. [10]

In addition, moon *Io* is both at a 1:2 *Laplace* resonance with *Europa*, and ten times relatively closer to its planet than the Moon is to *Earth* ($a_{Io} \sim 5.89R_J$). This leads to tidal deformations inside *Io* that produce extreme tectonics and volcanism. Neutral gas continuosly ejected by *Io* is ionized and accelerated by the fast-flowing Jovian magnetosphere, and made to corotate as a giant plasma

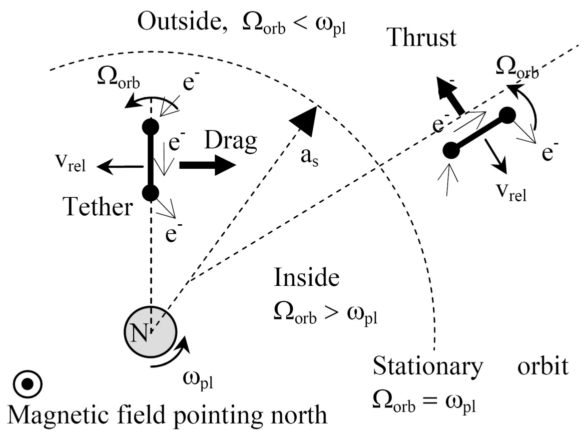

Figure 1: Tether operation inside/outside 'drag sphere'

torus, which is denser than the plasmasphere and reaches from about the plasmasphere to *Europa*, orbiting at $a_{Eu} \approx 9.38R_J$.

Tether drag/thrust will only be exerted within plasmasphere or torus; the tether current can be (nearly) shut off at convenience by switching off the HC or plugging a large resistance in the tether circuit. The proposed Jovian tour will exploit the positions of perifocus in the orbit coming from *Earth* and of perijove and apojove after capture, relative to the 'drag sphere', to exert either drag or thrust; notice that this sphere only roughly indicates whether drag or thrust applies in case of noncircular orbits.

The Jovian tour starts with a S/C approaching *Jupiter* at the relative velocity $\nu_\infty \sim 5.7km/s$ of a minimum energy transfer. Assuming the perifocus is at $r_p \sim 1.5R_J$ the hyperbolic excentricity is very small, $e-1 = \nu_\infty^2 r_p/\mu_J \approx 0.027$. After capture, closed orbits evolve under repeated Lorentz force, as schematically shown in Fig. 2.

Spacecraft capture requires drag to make a minimum work, this condition being roughly written as

$$\alpha \times LI_{a\nu}B \times \pi r_p = (1+\beta) \times \frac{1}{2}M_{S/C}\nu_\infty^2 \qquad (7)$$

If ohmic and HC contact impedances are neglected, the tether will be biased positive throughout its length and the averaged tether current is 2/5 of the OML current [7] at uniform bias $E_m L$,

$$I_{a\nu} = \frac{2}{5} \times \frac{2wL}{\pi} eN_e \sqrt{\frac{2eE_mL}{m_e}} \qquad (8)$$

Introducing the tape mass $m_t = \rho_t Lwh$, yields a mass ratio condition,

$$\frac{M_{SC}}{m_t} = \frac{8\alpha/5}{1+\beta} \times \frac{m_e N_e r_p \sqrt{2eE_mL/m_e} \times LeB/m_e}{\rho_t h \times \nu_\infty^2}$$

We take values $N_e \approx 10^3$ cm^{-3}, $B \approx 1.6$ gauss, $E_m \approx 4.8$ V/m at the perifocus r_p from the *Divine-Garrett* Jovian model [11], and introduce a factor $\alpha = 0.5$ to roughly account for variations along a drag path $\sim \pi r_p$. Capture requires a positive β; the greater is β the lower is the eccentricity of the capture orbit. Using $\beta = 3/4$ and an *Al* tape of thickness $h = 0.05$ mm and length $L = 50$ km, yields

$$M_{SC}/m_t \approx 4.15 \qquad (9)$$

For β barely positive, the mass ratio would be about 7.25. Note that the ratio M_{SC}/m_t is independent of tape width w and increases with the ratio $L^{3/2}/h$. There is a limit, however, to the possible gain in mass ratio because of the OML-to-short circuit current ratio

$$\frac{I(OML)}{I(shortcircuit)} \propto \frac{N_e\sqrt{E_m} \times wL^{3/2}}{\sigma_{cond}E_m wh} \qquad (10)$$

is also proportional to $L^{3/2}/h$. Increasing this ratio leads ultimately to a maximum current that the tape cross-section can carry, as ohmic limitation.

Setting tape width $w = 2$ cm leads to mass $m_t = 135$ kg, current $I_a v = 11.9$A, and $power I_{av} E_m L = 2.86$ Mw. For $\beta = 3/4$ and $\beta \approx 0$, we then have $M_{SC} = 560$ kg and 979 kg respectively. Masses, current and power scale linearly with w. In particular, taking $w = 5$ cm leads to masses $m_t = 337.5$ kg, and $M_{SC} = 1400$ kg and 2447 kg for $\beta = 3/4$ and $\beta \approx 3/4$, respectively.

The tether will serve as power source whenever an electric load is plugged in the tether circuit. Note that a power ~ 10 Kw, say, could be substracted from the several Mws produced during capture, with negligible effect on S/C dynamics. Tether current would be off along most of the elliptical orbits, following capture and succesive perijove passes, where the Lorentz force would be weak anyway. The current, however, could be switched on occasionally to generate power.

The orbital energy per unit mass reduced, at capture, in the amount $-(1+\beta)\frac{1}{2}\nu_\infty^2$, determines the semiaxis a_1 of the first elliptical orbit,

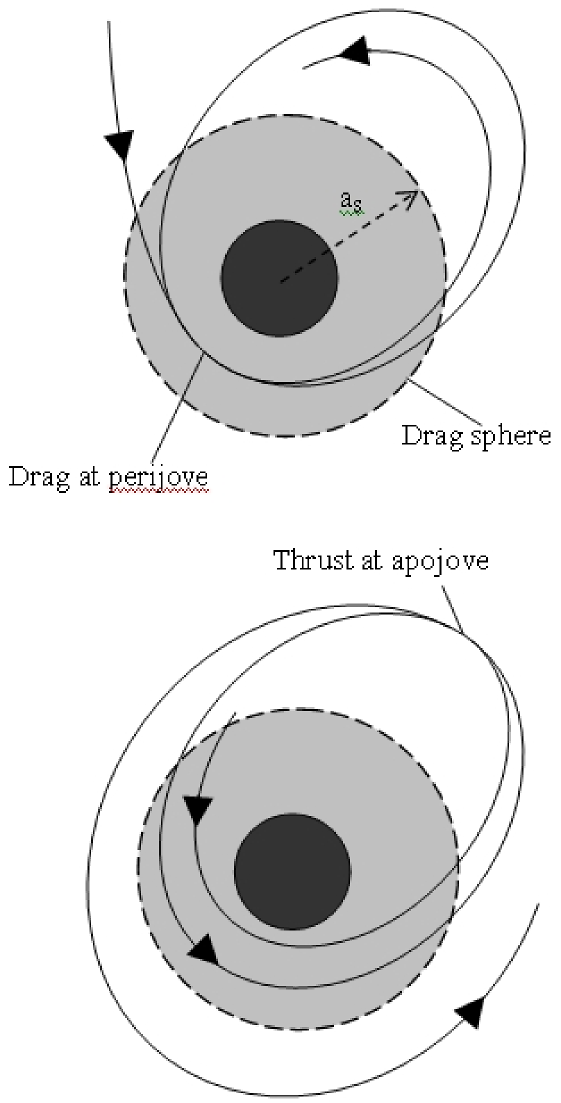

Figure 2: Phases: Capture and lowering apojove. Raising perijove.

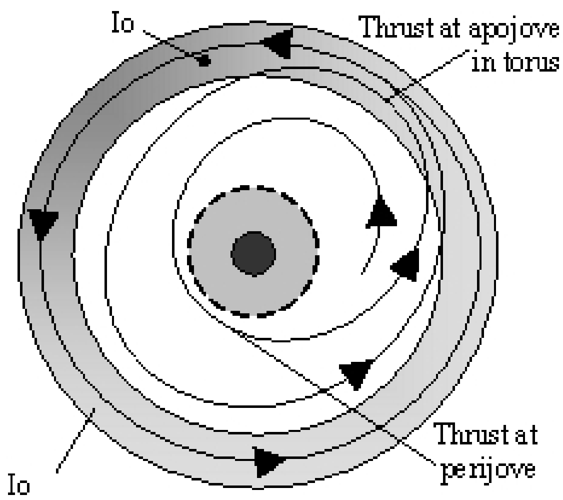

Figure 3: Spacecraft capture at Io

$$-\beta\nu_\infty^2/2 \equiv -\mu_J/2a_1$$

This yields $a_1 = 72.8R_J$, and an orbital period $T_1 = 76.5$ days. Lowering apojove can proceed fast; after the third perijove pass we find $a_3 = 12.8R_J$, $T_3 = 5.6$ days. The raising perijove phase, from $1.5R_J$ to $3R_J$, say, will take somewhat longer.

4. Capture into Low Io Orbit

Assume that in the raising perijove phase, the S/C has been carried to some circular orbit near the end of the plasmasphere, where both B and N_e are sensibly smaller than at capture conditions. Switching tether current on one side of the orbit leads to a sequence of elliptical orbits of fixed perijove but increasing apojove, which can get deep in the *Io* torus after multiple passes. Note that *Io*'s orbital period is only 1.77 days, the periods of those orbits increasing from under to over 1 day, the total duration of the above operation being actually short.

Now the dense, fast-flowing plasma torus can act as a 'filling station'. Switching current on around apojove, tether thrust can take the perijove itself deep into the torus. Finally, with current on and off conveniently, it would be possible to approach *Io* at a small relative velocity to allow it to capture the S/C. Note that the sphere of influence of Io against *Jupiter* is only 7200 km, *Io*'s radius itself being 1820 km. It may be necessary to finely tune tether thrust to keep a low orbit around *Io* stable.

The case for orbiting *Europa* is harder, just meaning that operations should take a sensibly longer time.

5. Conclusions

It appears possible to capture a S/C into orbit around *Jupiter*, and then make the S/C reach a low *Io* orbit, and possibly a low *Europa* orbit, by basically using an ED-tether. Important side issues requiring detailed consideration include tape heating at the intense current collection; S/C survival, under radiation, through the inner Jovian belts and around the moons; and keeping tape dynamics controlled under the low *Jupiter*'s gravity gradient.

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